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# An Experimental Evaluation of Flammable and Non-Flammable High Pressure HFC Replacements for R-22

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# AN EXPERIMENTAL EVALUATION OF FLAMMABLE AND NON-FLAMMABLE HIGH PRESSURE HFC REPLACEMENTS FOR R-22

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## ABSTRACT

In this paper, the performance of three high pressure HFC refrigerants: R-32, R-410A, and R-410B, is compared to that of R-22. R-32 has excellent thermophysical properties as compared to R-410A, R-410B and R-22. However, R-32 is a flammable refrigerant while R-410A and R-410B are non-flammable. The performance of these refrigerants is investigated in a residential heat pump at the test conditions specified in ASHRAE Standard 116-1983. Overall the high pressure fluids performed better than R-22, with R-32 giving the best results. R-32 has a cooling seasonal performance that is 5.1% better than R-22 and a heating seasonal performance that is 2.5- 4% better than R-22. R-410A and R-410B have cooling seasonal performances which are 2-3% better than R-22, and heating seasonal performances that are similar to that of R-22.

## NOMENCLATURE

| | |
|---|---|
| 17L | Low Temperature Heating Test based on ASHRAE Standard 116-1983 |
| 35F | Frost Accumulation Test based on ASHRAE Standard 116-1983 |
| 47S | High Temp Heating Test based on ASHRAE Standard 116-1983 |
| ASHRAE | American Society for Heating, Refrigerating & Air-Conditioning Engineers |
| ARI | American Refrigeration Institute |
| CFCs | Chlorofluorocarbons |
| COP | Coefficient of Performance |
| G.W.P. | Global Warming Potential |
| HCFCs | Hydrochlorofluorocarbons |
| HFCs | Hydrofluorocarbons |
| HSPF | Heating Seasonal Performance Factor |
| O.D.P. | Ozone Depletion Potential |
| R-22 | Refrigerant 22, Trifluoromethane |
| R-32 | Refrigerant 32, Difluoromethane |
| R-410A | R-32/R-125 ( 50/50 wt.% ) |
| R-410B | R-32/R-125 ( 45/55 wt.% ) |
| $P_{cond}$ | Condensing Pressure |
| $P_{evap}$ | Evaporating Pressure |
| SEER | Seasonal Energy Efficiency Ratio |
| ST | Short Tube Restrictor |
| TEV | Thermostatic Expansion Valve |

## INTRODUCTION

Environmental concern over the depletion of stratospheric ozone has resulted in restrictions in the production and the phase-out of chlorofluorocarbons (CFCs) and hydrofluorocarbons (HCFCs). HCFC-22 is widely used in the air-conditioning and heat pump industry, especially in residential unitary and air-conditioning systems. The phaseout of HCFC-22 requires manufacturers to find suitable alternatives in a relatively short time frame. In the search for alternatives, the evaluation of the overall performance of the candidate refrigerants is very important. Three high pressure replacement refrigerants (flammable and non-flammable) were selected: R-32, R-410A and R-410B. Although flammable, R-32 is investigated because it represents a theoretical upper limit of performance (Domanski, 1995). This study experimentally investigates the steady state and cyclic performance of these refrigerants.

## TEST FACILITY AND TEST UNIT

A psychrometric type test facility was designed and built to measure the steady state and cyclic performance of an air-to-air heat pump. The test chambers can simulate the cooling and heating test conditions as defined by ASHRAE Standard 116-1983. The test unit was a split heat pump system having a nominal capacity of 7.0 kW. The test unit used a reciprocating compressor and two expansion devices. The expansion device for the cooling mode was a short tube restrictor (ST) and the expansion device for the heating mode was a thermostatic expansion valve (TEV). R-22 was tested with the original compressor and TEV, while the high pressure refrigerants were tested with a compressor and TEV which were designed for the higher operating pressures. As compared to the original compressor, calorimeter tests performed by the compressor manufacturer with R-410A showed that the high pressure compressor had a 4% lower efficiency at 54.4 °C condensing temperature and a 7% higher efficiency at 37.8 °C condensing temperature.

## PERFORMANCE MEASUREMENT AND TEST PROCEDURE

### Capacity Measurement

The experiments to measure the capacity and COP were performed based on ASHRAE Standard 116 (ASHRAE, 1983), and ARI Standard 210/240 (ARI, 1989). In this study, the air-side capacity and the refrigerant-side capacity were measured.

The loop air enthalpy method was used to measure the air-side capacity. In measuring the air-side capacity, the air flow rate and air enthalpy difference between inlet and outlet of the indoor coil were measured. The air flow rate was measured by a nozzle apparatus. In measuring the refrigerant-side capacity, the refrigerant mass flow rate and the refrigerant enthalpies at the inlet and outlet of the heat exchanger were used. The mass flow rate was measured by a coriolis type mass flow meter, and the refrigerant enthalpies were calculated by REFPROP V4.01 (Gallagher et al. 1993) from the temperature and pressure measurements. ASHRAE Standard 116 requires that the capacities determined using these two methods should agree within 6% of each other. The two methods agreed within 3% for all tests conducted in this study.

### Soft Optimization

The experimental results of this study for R-22, R-410A and R-410B are obtained from Hwang et al., 1995. Except for the ST and charge optimization, the R-22 tests were conducted without making any modifications to the system. The high pressure refrigerants were tested after installing the TEV and compressor specifically made for the higher operating pressures, changing the lubricant from mineral oil to ester oil, and changing the filter drier. A soft optimization was conducted for all refrigerants tested to maximize both the cooling and heating COP. At first, the optimum charge for heating was obtained by changing the refrigerant charge at the 47S heating test conditions. The optimum charge was chosen such that the maximum COP could be obtained. To find the ST for the cooling mode that corresponds with the optimum charge in the heating mode several charge optimization tests were run with different size STs at the cooling test conditions. R-22 was optimized at the ASHRAE A test condition, while R-32, R-410A and R-410B were optimized at the ASHRAE B test condition. Initially, the ASHRAE A test condition was used for the R-22 charge optimization because it is the capacity rating point. However, the change to the ASHRAE B test condition was made for the high pressure refrigerants' charge optimization since this test condition has a more profound effect on the cooling seasonal performance than does the ASHRAE A test condition.

## HIGH PRESSURE REFRIGERANTS INVESTIGATED

The three high pressure refrigerants investigated are non-ozone-depleting substances, as shown in Table 1. R-32 has a higher latent heat and higher heat capacities as compared to R-22. The higher latent heat leads to higher system capacity for the same sized compressor. The two binary mixtures (R-410A and R-410B) also have a higher latent heat and heat capacity than that of R-22. The saturated vapor density of the binary mixtures is approximately 44% higher than that of R-22, which also translates into higher capacities for the same sized compressor. Hence, to test R-32 and the binary mixtures with the original heat exchangers, the displacement of the compressor had to be reduced to achieve similar capacities. The high pressure fluids have a higher vapor pressure by approximately 60%, as compared to R-22, but the slope is quite similar to that of R-22 in the temperature range of interest. Therefore, the pressure ratio of these refrigerants is expected to be similar to that of R-22.

**Table 1.** ENVIRONMENTAL AND SAFETY PROPERTIES OF REFRIGERANTS INVESTIGATED

| Refrigerant | R-22 | R-32 | R-410A | R-410B |
|---|---|---|---|---|
| Components | HCFC-22 | HFC-32 | HFC-32/125 (50/50 wt.%) | HFC-32/125 (45/55 wt.%) |
| O.D.P.(CFC-11=1.0) | 0.055[1] | 0 | 0[2] | 0[3] |
| G.W.P. ($CO_2$= 1.0) | 1600[1] | 580[4] | 2200[2] | 2020[3] |
| Flammability | No | Yes | No | No |

**Table 2.** THERMODYNAMIC PROPERTIES OF REFRIGERANTS INVESTIGATED

| Refrigerant | | R-22 | R-32 | R-410A | R-410B |
|---|---|---|---|---|---|
| Molecular Weight | [g/mol] | 86.5 | 52.0 | 72.6[2] | 75.6[3] |
| Normal Boiling Point | [°C] | -40.9 | -51.8 | -52.7[2] | -51.8[3] |
| Critical Temperature | [°C] | 96.2 | 78.2 | 72.5[2] | 71.6[3] |
| Critical Pressure | [bar] | 50.5 | 57.9 | 49.5[2] | 47.8[3] |
| Latent Heat | at 25 °C [kJ/kg] | 180.6 | 271.9 | 194.0 | 184.9 |
| Bubble Pressure | at 25 °C [bar] | 10.4 | 16.9 | 16.5 | 16.4 |
| Liquid Density | at 25 °C [kg/m$^3$] | 1192 | 961 | 1083 | 1096 |
| Sat.Vapor Density | at 25 °C [kg/m$^3$] | 44.5 | 47.2 | 62.2 | 64.5 |
| Temperature Glide | at 1 atm [K] | 0.0 | 0.0 | 0.1 | 0.1 |
| Sat. Liq. Heat Capacity | at 10°C [kJ/kg K] | 1.23 | 1.79 | 1.48 | 1.46 |
| Sat. Liq. Heat Capacity | at 50°C [kJ/kg K] | 1.47 | 2.43 | 1.92 | 1.89 |

[Source] REFPROP V4.01 (Gallagher et al. 1993) unless otherwise noted.
1: DuPont, 1994
2: Allied Signal, 1995
3: DuPont, 1995
4: Calm, 1995

## TEST RESULTS AND DISCUSSION

**Soft Optimization Test Results**

The soft optimization tests were carried out with the refrigerants R-22, R-32, R-410A, and R-410B. The results of the soft optimization for the refrigerants tested are arranged in Figures 1 through 4. Figures 3 and 4 show the charge optimization curves for R-32, R-410A and R-410B at ASHRAE B test conditions using the ST sizes given in Table 3. R-22 charge optimization is not shown in these two figures because it was carried out at the ASHRAE A test conditions, as discussed earlier. The results of the soft optimization tests are shown in Table 3. For R-32 and R-410A, it was not possible to adjust the charge and ST so that the optimum charge for heating and cooling test conditions was the same. Hence, for R-32 and R-410B, the average between the optimum heating and cooling charges was used. For R-32, the ST size for the optimum charge, 1.35mm, is much lower than that for the other refrigerants. This is due to the fact that a lower mass flow rate is required because of the higher latent heat of R-32 in comparison to the other refrigerants (refer Table 2). When the optimum charge (for best COP) was the same for the different sized STs as in the case of R-410B, the subcooling and superheat were evaluated in choosing the optimum ST size. The optimum charge for R-32 is much lower than that for R-22, R-410A, and R-410B. This is because of the lower molecular weight of R-32.

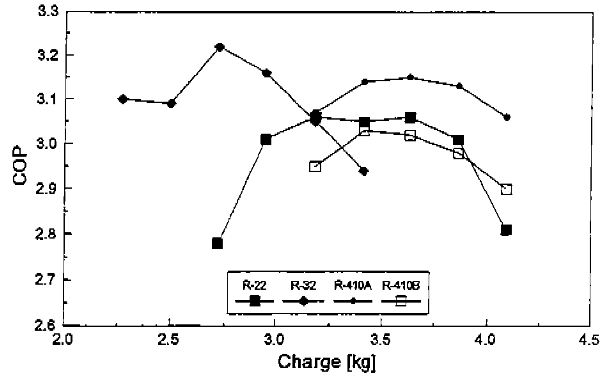


**Figure 1.** R-22, R-32, R-410A & R-410B CHARGE VS. COP AT HEATING TEST 47S

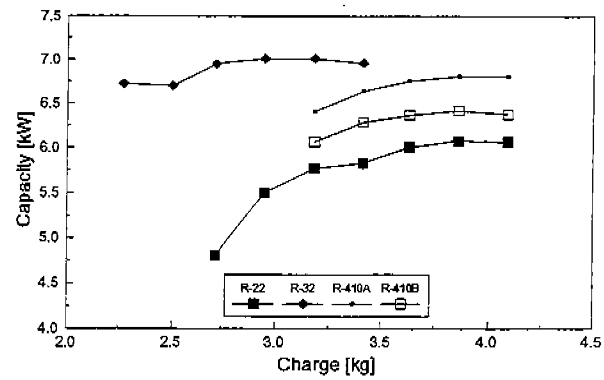


**Figure 2.** R-22, R-32, R-410 & R-410B CHARGE VS. CAPACITY AT HEATING TEST 47S

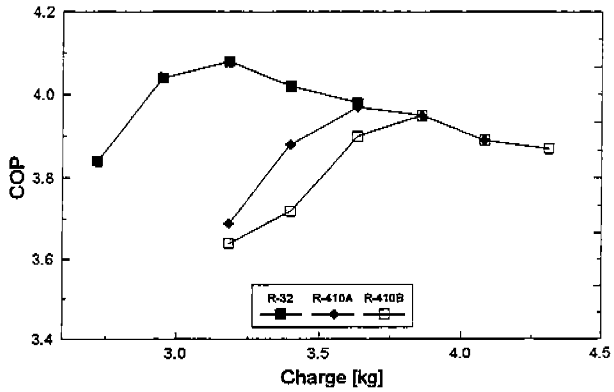


**Figure 3.** R-32, R-410A & R-410B CHARGE VS. COP AT COOLING TEST B

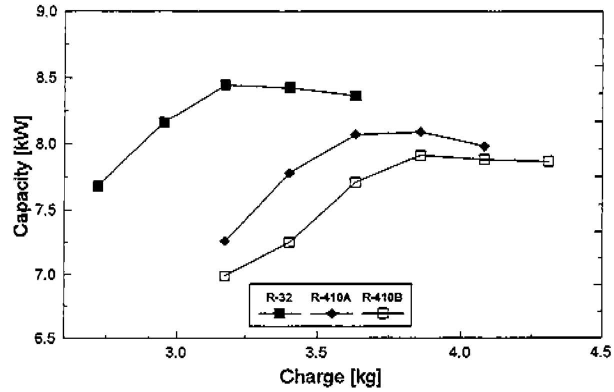


**Figure 4.** R-32, R-410A & R-410B CHARGE VS. CAPACITY AT COOLING TEST B

**Table 3.** OPTIMUM CHARGE FOR EACH OPERATING MODE

| Refrigerant | R-22 | R-32 | R-410A | R-410B |
|---|---|---|---|---|
| Heating Optimum Charge [kg] | 3.6 | 2.7 | 3.6 | 3.4 |
| Cooling Optimum Charge [kg] | 3.6 | 3.2 | 3.6 | 3.8 |
| ST Size [mm] | 1.65 | 1.35 | 1.55 | 1.55 |

**Steady State Performance Results**

After the soft optimization tests, ASHRAE tests were carried out with the optimum refrigerant charge and ST. The capacity and COP are compared in Tables 4, 5, and 6.

R-32 showed the highest cooling and heating capacities, and the highest COP's in both the cooling and the heating cases. The cooling capacity was higher by up to 12.2% as compared to that of R-22 eventhough a smaller compressor was used. The cooling COP was higher by up to 6.1% as compared to R-22. The heating capacity was higher by 13.9% at 47S and by 29.2% at the 17L test. R-410A and R-410B show similar cooling and heating performances with each other. The two binary mixtures showed cooling capacities that were 4-7% higher than that of R-22 in spite of the smaller compressor. The cooling COP of R-410A and R-410B was also higher by 2-4% as compared to that of R-22. These mixtures also had better heating capacities by 3-6 % at 47S and by up to 20% at the 17L test. As expected, all the high pressure refrigerants had higher evaporating and condensing pressures by approximately 60% as compared to those of R-22, and the pressure ratios were nearly the same as that for R-22.

**Table 4.** ASHRAE COOLING A TEST RESULTS

| ITEM | R-22 | R-32 | R-410A | R-410B |
|---|---|---|---|---|
| Capacity [kW] | 6.82 | 7.65 | 7.16 | 7.07 |
| COP | 3.20 | 3.31 | 3.25 | 3.23 |
| $P_{cond}$ [kPa] | 1641.8 | 2705.9 | 2611.8 | 2587.3 |
| $P_{evap}$ [kPa] | 707.5 | 1129.9 | 1097.1 | 1081.1 |
| Pressure Ratio | 2.32 | 2.39 | 2.38 | 2.39 |

**Table 5.** ASHRAE HEATING 47S TEST RESULTS

| ITEM | R-22 | R-32 | R-410A | R-410B |
|---|---|---|---|---|
| Capacity [kW] | 6.13 | 6.98 | 6.51 | 6.29 |
| COP | 3.13 | 3.15 | 3.02 | 3.03 |
| $P_{cond}$ [kPa] | 1678.5 | 2681.3 | 2618.0 | 2435.1 |
| $P_{evap}$ [kPa] | 494.6 | 811.8 | 826.3 | 812.8 |
| Pressure Ratio | 3.39 | 3.30 | 3.17 | 3.00 |

**Table 6.** ASHRAE COOLING B TEST AND HEATING 17L TEST RESULTS

| ITEM | R-22 | R-32 | R-410A | R-410B |
|---|---|---|---|---|
| "B" Capacity [kW] | 7.34 | 8.12 | 7.83 | 7.64 |
| "B" COP | 3.78 | 4.01 | 3.92 | 3.88 |
| "17L" Capacity [kW] | 2.77 | 3.58 | 3.32 | 3.33 |
| "17L" COP | 1.97 | 1.95 | 1.87 | 1.89 |

**Seasonal Performance Results**

When evaluating the overall performance of heat pumps including the steady state and cyclic performances, the seasonal performance factors, SEER and HSPF are used. These factors are important because they approximate operation over an entire season. The seasonal performance was calculated based on ASHRAE Standard 116 (ASHRAE, 1983). Eight different ASHRAE test results including the steady state and cyclic performances were used in this calculation. The HSPF is calculated for all the six different climatic regions specified in the ARI Standard 210/240.

The seasonal performance factors for each refrigerant are calculated and compared in Table 7. Relative to R-22, R-32 has a 5.1% higher SEER and a 2.5-4% higher HSPF. The higher SEER is due to the better cooling capacities and COPs of R-32. The higher HSPF is due to the better 47S cooling capacity and COP, and a better cyclic performance. R-410A has a 2.6% higher SEER and 1-2% lower HSPF and R-410B has a 1.7% higher SEER and 0-2% higher HSPF. The two binary mixtures have lower COP for 47S test conditions but their better cyclic performance contributes to their having similar HSPFs.

**Table 7.** SEASONAL PERFORMANCE TEST RESULTS

| ITEM | R-22 | R-32 | R-410A | R-410B |
|---|---|---|---|---|
| SEER [Btu/kWhr] | 11.68 | 12.33 | 12.02 | 11.91 |
| HSPF (Region I) | 2.41 | 2.50 | 2.38 | 2.42 |
| HSPF (Region II) | 2.35 | 2.42 | 2.31 | 2.35 |
| HSPF (Region III) | 2.24 | 2.31 | 2.21 | 2.25 |
| HSPF (Region IV) | 2.01 | 2.09 | 2.01 | 2.04 |
| HSPF (Region V) | 1.72 | 1.76 | 1.70 | 1.73 |
| HSPF (Region VI) | 2.38 | 2.46 | 2.35 | 2.39 |

[Note] 1. Conditions in SEER calculation.
(1) Oversize factor: 10%
(2) Design temperature of 35 °C (95 °F) (needs eight temperature bins ranging from 18 °C (65 °F) to 41 °C (105 °F).
(3) The bin hours based on the U.S.A. national average climate.
(4) The building load (BL) was selected from the R-22 baseline case for fair comparison.
2. Conditions in HSPF calculation
(1) Eighteen temperature bins are used, ranging from -32 to 18 °C (-25 to 65 °F).

## CONCLUSIONS

All the three high pressure refrigerants investigated show improved steady-state and seasonal performances in comparison to R-22. R-32 shows the best results, with the highest seasonal performances. This was as expected, due to the excellent thermophysical properties of R-32. However, R-32 is flammable and hence does not find favor in the industry. All of these high pressure replacement refrigerants require careful design considerations due to the much higher operating pressures. Furthermore, it should be noted that the improvement in performance may be even larger if the system is designed specifically for these refrigerants.

## ACKNOWLEDGMENTS

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